Evaluation of geometrically calibrated segment lengths: preliminary results on inter-hip, femur and shank cases

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Introduction

Geometry of biomechanical models can be personalized through different approaches based on palpated anatomical landmarks, regression equations, reconstructed medical imaging, or optimization relying on optoelectronic data. The latter offers great perspectives since it is faster and lighter than imaging procedures, does not necessitate additional data acquisition and can also correct misplaced markers. In such geometric calibration methods, an osteo-articular model is defined, describing distances and degrees of freedom (DoFs) mimicking joint functions. These quantities can be calibrated to fit optoelectronic data through optimization methods minimizing the reconstruction error1–3. However, validation of the calibrated quantities remains an issue.

Research Question

Do geometric calibration methods guarantee consistent anatomical lengths compared to medical imaging assessment ?

Methods

Optoelectronic data (200Hz) of functional motions - activating each DoF of the lower limb - of 7 subjects were recorded. Marker trajectories were smoothed through moving average over five frames. A 33 DoFs musculoskeletal model of lower limbs, trunk and head was used. The lower limb4 exhibited 3 DoFs at hip, 1 DoF at the knee, and 2 intersecting DoFs at the ankle. Firstly, a regression method (RM) linearly scaled with subjects' height initially estimated the segment lengths. Secondly, geometric calibrations (GCn) with RM as an initial guess optimized segment lengths, positions of joint centers, and marker positions1 by minimizing Euclidian distances between measured and reconstructed markers. Different number of frames equally spaced in the motion data - n = {3, 10, 50, 100, 500} - were used to test the efficiency of the method.

Reference joint center positions (two hips, two knees, two ankles) were obtained through the EOS® system. For that purpose, the same subjects underwent biplanar radiographs allowing 3D reconstruction of the pelvis, femurs, tibias, fibulas and spine. Reference hip joint centers were defined as the centers of the spheres fitted on the meshes of the femoral heads5. The knee joint centers were defined as the midpoints between the two centers of spheres fitted on both condyles of the femurs6. Finally, the ankle joint centers were defined as the midpoints between distal nodes of tibias and fibulas.

Inter-hip, femur, and shank (left and right) lengths were computed for each method (RM, GCn, EOS). Normality of the data was not systematically ensured by Shapiro-Wilk test. Thus, the non-parametric Friedman's test was used to check if the quantities of the seven methods were significantly different ($p<0.05$). If this hypothesis was ensured, Fisher's LSD tests were applied to detect significant differences among methods (RM, GCn) compared to EOS.

Results

Method	Inter-hip	Left Femur	Right Femur	Left Shank	Right Shank
RM	157.7*** ± 6.5	449.3 ± 18.5	449.3** ± 18.5	453.4*** ± 18.7	453.4*** ± 18.7
GC_3	160.6** ± 7.9	444.9 ± 16.0	440.3 ± 21.2	446.1** ± 24.1	452.5*** ± 22.4
GC_{10}	164.6* ± 8.8	443.5 ± 18.0	443.3 ± 23.3	447.8*** ± 24.2	447.6** ± 18.3
GC_{50}	167.8 ± 11.0	442.6 ± 18.4	444.0* ± 21.2	446.9* ± 24.8	447.7** ± 21.3
GC_{100}	166.9 ± 9.0	442.8 ± 18.8	444.3* ± 21.8	446.7** ± 25.4	447.3* ± 22.0
GC_{500}	167.8 ± 11.2	442.8 ± 18.5	444.3* ± 20.8	446.5** ± 24.5	447.0* ± 21.8
EOS	172.3 ± 14.3	440.8 ± 18.5	438.0 ± 18.7	418.1 ± 23.8	419.5 ± 24.3

Tab 1 : Mean values of the distances and standard deviation in mm. RM: Regression method, GC_n: geometrical calibration with n frames, EOS: measured value. Fisher's LSD test results are provided: *p<0.05, **p<0.005, ***p<0.001

Results are presented in Table 1. First, no significant difference among methods was found for the left femur length assessment. Indeed, the mean distance between EOS and RM was 8.5 ±10 mm, and the mean difference between EOS and GCn was between 4.1 ±7.4 mm (GC3) and 1.8 ±7.8 mm (GC50). Right femur and inter-hip lengths estimations were significantly different among methods. Fisher's LSD test revealed significant differences for the right femur length between EOS, RM and GC50,100,500, with mean differences with respect to the EOS reference data ranging from 2.3±6.3 mm (GC3) to 11.3±10.5 mm (RM). EOS inter-hip length was significantly different when assessed from RM and GC3,10 and mean differences to EOS data ranged between -14,5 ±10.6 mm (RM) and -4.47 ±11.4 mm (GC500). Also, significant differences between methods were found for both shanks, Fisher's LSD test revealed significant difference between EOS and each method. The mean errors for these segments ranged between 28.84 ± 5.83 (GC50) and 35.33 ±12.31 (RM) for the left shank and between 33.9 ±12.06 (RM) and 27.46 ± 6.01 (GC500) for the right side.

Discussion

The results of GCn are promising since it reduced systematically the segments lengths differences compared with the EOS reference data. However, the number of frames used in GCn influenced the results. For inter-hip length and left femur, increasing n tended to minimize significantly the distance to EOS until GC50. For the right femur, the GC3 gave better results but might be a local minimum. This approach seems to give good results compared to regression and functional methods such as sphere fitting to estimate the hip position7. However, GCn didn't matched the measured anatomical length of the shank. Only 7 subjects were involved but the difference was systematic, requiring further investigations to be explained. However, the comparison of the different methods, based on segment length estimation, should be completed by a comparison of joint center position assessment in the segments' local coordinate system.

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